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PROJECT MICHAEL

CONTRACT N6-ONR-27135

COLUMBIA UNIVERSITY

HUDSON LABORATORIES

DOBBS FERRY, N. Y.

RESEARCH SPONSORED BY

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COLUMBIA UNIVERSITY

Hudson Laboratories

Dobbs Ferry, N. Y.

PROJECT MICHAEL

Contract N6-ONR-27135

STATUS REPORT

October 1, 1953
to
March 31, 1954

W. A. Nierenberg
Director

Research Sponsored by
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COLUMBIA UNIVERSITY
HUDSON LABORATORIES
STATUS REPORT, OCT. 1 - MAR. 31, 1954

SUMMARY

1. A continuous series of submarine canyons about 100 fathoms deep, separated by ridges 2-3 miles wide have been found on sonic sounding records taken parallel to the north coast of Puerto Rico in 100 and in 600 fathoms of water.

2. Analysis of refraction profiles near the hydrophones of the San Juan installation has shown the bottom to be highly irregular with a complex fault system present. The basement is at about 10,000 ft and has a velocity of 20,000 ft/sec.

3. The analysis of sound range data at Puerto Rico has led to the following results:

   a) The total energy crossing a unit area, in the frequency band 53-106 cps, was found for three runs along 000°T. Differences of 2 to 3 db in the results from runs recorded on the deep moving coil and barium titanate hydrophones were shown to be due to differences in hydrophone calibrations.

   b) Along 000°T, the pressure level vs range curve was 2 to 3 db higher for the 212-425 cps band than for 53-106 cps over most of the 60 kyd range.

   c) In the frequency range 18.8 to 1200 cps, a plot of total energy crossing a unit area against range was made for distances along 000°T out to 220 kyds.

   d) The ratio of the pressure level at the second deep water focusing peak to the pressure level at the first peak was much smaller for a run along 34°T which passed over a seamount than for a run along 000°T which did not.

4. In a joint operation with Woods Hole Oceanographic Institution, experimental investigations of sound propagation along the Puerto Rico trench and up the slope were made. The surface dipole effect was also studied.

5. Sound propagation studies were conducted in the shallow water south of St. Thomas in the Virgin Islands with continuous wave and shot sources:

   a) Pressure level-range data were obtained for frequencies from 7-1/2 to 35 cps in 2-1/2 cps steps out to 4000 yds at the highest frequencies.

   b) A suspension system was devised which permitted the hydrophones to be towed at 5-6 knots without excessive self-noise.

   c) From the shot runs, the variation of sound velocity with frequency was determined and the Airy phase recorded.

   d) A prediction that a sound source with the same power output at every frequency will produce a higher pressure level at the Airy phase frequency than at any other was confirmed.

6. The ambient noise in the deep sound channel was recorded in the Tongue of the Ocean in the Bahamas and east of Eleuthera.

7. Ambient noise measurements made in Lake Pend Oreille, Idaho, indicated the broad-band ambient noise level in the lake is 10 to 20 db below that of the ocean at sea state 0 to 1.

8. The lower half of the seamount chain arcing south from Cape Cod to Bermuda was surveyed. A new seamount was discovered and significant soundings made across several others.

9. Transmission data taken in December, 1952, on the continental shelf south of Montauk Point, Long Island, have been analyzed:

   a) In the frequency range 30-60 cps, the loss per reflection for bottom reflections at angles beyond the critical angle is not greater than 0.25 db.

   b) For the frequency ranges 30-60 cps and 60-120 cps, the pressure level-range curves are relatively flat out to 145 kyds. This indicates surface sound channel propagation is unimportant at these low frequencies.

c) In the three octave bands between 250 cps and 2000 cps the pressure levels slowly decrease from 30 kyds to 115 kyds and then drop rapidly out to a maximum range of 145 kyds. The drop is attributed to the loss of the surface sound channel transmission.

10. A new listening device, the "bedspring" or "grandstand" array was described. This instrument should have a detecting range three to ten times that of present arrays.

11. Tests of a redesigned "Yo-Yo" listening unit were made during March, 1954. A submarine was tracked 16 miles without difficulty. The single "Yo-Yo" used in these tests operated for its full design lifetime.

12. The anchored buoy, a device designed to eliminate expensive armored cables used at permanent listening stations, was successfully tested in March. A submarine was tracked 20 miles and shots were recorded.

INTRODUCTION

The major effort of Hudson Laboratories has been devoted to studying low frequency sound propagating through the ocean. During the past six months, these studies have progressed considerably. Investigations of sound transmission in both deep and shallow water were conducted and devices directly useful in naval operations, tested.

Deep ocean sound research of Hudson Laboratories continued to be centered on the permanent installation at San Juan, Puerto Rico. The properties of the station as a listening site were examined further. Although no new refraction runs were made, a careful analysis of old records showed that the subsurface beds are many and complex. A fairly complete map was drawn of 53-106 cps sound transmission in the area; along one azimuth, this map extended to 740 kyds. Evidence for the "shadow" effect of a seamount was found. In a joint operation with the Woods Hole Oceanographic Institution (WHOI), (March, 1954), sound propagation in the Puerto Rico trench and up the slope were studied and the surface dipole effect investigated.

Studies of the ambient noise limitation on passive detection shifted to deep water in this period. Measurements were made with "Duckling" hydrophones in the deep sound channel east of Eleuthera and in the Tongue of the Ocean in the Bahamas.

A scheme for allowing submerged submarines to communicate via the sound channel was suggested and analyzed theoretically.

The USS ALLEGHENY made a sonic sounding cruise (October and November, 1953) along the seamount chain arcing southward from Cape Cod to Bermuda. A new mountain, Mount Michael, was discovered and another, Seamount George, was surveyed for the first time. Significant sounding lines were carried across eight other seamounts.

During January and February, 1954, sound propagation was investigated in the shallow water south of St. Thomas in the Virgin Islands. With A Mark 6(b) sources carried by the ALLEGHENY and a listening hydrophone towed by a small boat, intensity-range data out to 4000 yds were obtained for frequencies of 7-1/2 to 35 cps every 2-1/2 cps. Subbottom conditions were determined by shooting refraction profiles. The shot records also gave the variation of sound velocity with frequency.

Experiments at the San Juan installation, March, 1954, included successful tests of two devices designed directly as operational instruments. One of these, the Yo-Yo is a sonobuoy which can listen in or below the surface sound channel. The other, the anchored buoy, permits the use of inexpensive wire with a deep water hydrophone. Both tracked a snorkeling submarine 16 to 20 miles in spite of the noise inherent in the San Juan location.

SOUND PROPAGATION STUDIES - SAN JUAN STATION

The San Juan installation of Hudson Laboratories is important as one of the few permanent listening stations available for scientific study of sound propagation in the deep ocean. Data gathered at such a station are most useful when they are correlated with theoretical predictions; but, sensible predictions can only be made if the physical properties of the water, bottom, and subbottom layers are known. During the past six months, additional investigations of these properties have been completed.

Continuous sonic soundings were obtained along two east-west zones parallel to the north coast of Puerto Rico off San Juan in 100 and 600 fathoms of water respectively. Every traverse shows a continuous series of submarine canyons about 100 fathoms deep, separated by ridges 2-3 miles wide and debouching northward toward the Puerto Rico trench. One of these canyons appears to be a rejuvenated canyon that has been flushed out recently by a turbidity current. Additional records obtained in March, 1954, are being analyzed and a large scale chart of the area north of San Juan will be prepared.

Attempts to determine the thicknesses and sound velocities of the subbottom beds off San Juan by refraction shooting have been only partially successful. The bottom appears to be highly irregular with a complex fault system present. Near the deep hydrophones (470 fathoms), no two refraction profiles show the same bottom speed and hydrographic charts indicate irregular patches of mud and rock. Beneath the deep hydrophones, the bottom is probably mud 500 to 700 ft thick with a velocity of 5300 ft/sec. The basement velocity is greater than 20,000 ft/sec. A profile shot east-west across the shallow hydrophones (200 fathoms) gave consistent results (Fig. 1). The indicated basement speed is 20,500 ft/sec at a depth of 9900 feet.

During 1953, the low frequency sound propagation properties of the San Juan area were determined by firing charges along several azimuths centered at the deep hydrophones. A large part of the data has now been analyzed. The total energy crossing a unit area was found in the frequency band 53-106 cps for three runs along azimuth 000°T. A typical curve, with a 740 kyd maximum range, is shown in Fig. 2. Differences of 2 to 3 db in the results from runs recorded on the deep moving coil and barium titanate hydrophones were attributed to differences in hydrophone calibrations. This explanation was confirmed by recording shots simultaneously on both hydrophones.

A few shots along 000°T were also analyzed in the 212-425 cps band. The pressure level vs range curve was 2 to 3 db higher over most of the 60 kyd range than that for the 53-106 cps band but the shapes were similar.

In the frequency range 18.8 to 1200 cps, the total energy per cycle crossing a unit area for runs along 000°T was determined as

$$10 \log \frac{\int_0^T p^2 dt}{\Delta f}$$

and plotted against distance out to 220 kyds (Fig. 3). Here p is the pressure level and Δf the frequency band. For this analysis, Δf was made a half-octave. This method of presenting data was suggested by Dr. J. B. Hersey of the Woods Hole Oceanographic Institution. As results become available, Fig. 3 will be extended to the full 740 kyds, and similar plots will be made for individual ray path arrivals.

During a run along 34°T, the firing ship passed directly over a seamount 130 kyds from the hydrophone (Fig. 4). In this case, the ratio of the pressure level at the second deep water focusing peak to the pressure level at the first peak is much smaller than for 000°T runs indicating that the seamount interrupted rays which would otherwise have reached the hydrophone.

For simplicity, theoretical treatments of sound propagation in a deep ocean have usually been based on a ray approximation. To make the theory check the experimental results, several corrections must be applied. During March, 1954, a combined operation was conducted by Hudson Laboratories and Woods Hole Oceanographic Institution to evaluate two of the corrective terms; the surface dipole effect and the loss of energy in multiple reflections up the slope. The surface dipole effect is due to the addition to the direct positive arrival of a negative surface-reflected arrival. The separation of the two arrivals depends on the depth of the source. The second effect, loss of energy on the slope, is very important at San Juan, since no sound from the deep ocean can reach the hydrophones without bouncing on the slope.

In the surface dipole experiment, shots were fired at several depths with one listening ship so close to the firing vessel (within three miles) that the direct arrival was well separated from ocean bottom reflections. A second listening ship was 34 miles away, near the first deep sound channel focusing peak. All

three ships were in deep water over the Puerto Rico trench. Similar data were obtained with listening ships at 500 and 1500 fathoms on the slope.

In the slope runs, the listening ships (WHOI BEAR and ATLANTIS) occupied stations at 500, 1000, 1500 and 2000 fathoms due north of the deep hydrophones while the firing ship (USS ALLEGHENY) moved out 60 miles and returned. The sound energies recorded with ship-borne hydrophones will be compared with previous results from the deep hydrophones. A 140 mile shot range run made during this same operation over the flat and very deep bottom of the Puerto Rico trench will give comparison data unaffected by attenuation in slope bounces.

At present, neither the shallow nor the deep San Juan hydrophones are useable. Electrical measurements of three kinds (March, 1954) indicated short circuits in the cables. A subsequent visual examination showed that both hydrophone armored cables had been broken by near-shore wave action. The severed ends of the cables were brought to the surface and tested. All hydrophones appeared to be intact. A temporary splice was made and the deep (470 fathom) barium ' tanate hydrophone put into operation. Although shots and sh , ncise were heard, the 60 cps background was unmanageably high. It is planned to repair the cables before summer.

PROPAGATION OF SOUND IN SHALLOW WATER

The properties of sound propagation in shallow water are in some respects more complex than those involved in deep water propagation. Because operating in the shallow water of continental shelves, harbors, and bays is of increasing importance to those charged with mine and submarine warfare, Hudson Laboratories has engaged in a limited shallow water sound propagation program. Experiments at three locations have been completed: two of these conducted near New York City were described previously; the third was carried out during January and February, 1954, south of St. Thomas in the Virgin Islands.

The area chosen for the operation has a flat coral bottom covered by 120 ft of water. Since the propagation of sound in shallow water depends as much on subbottom conditions as those of the water, the nature of the beds underlying the bottom was determined. Two mutually perpendicular refraction profiles were shot using a buoy laid by the U. S. Coast Guard as operations center. After preliminary analysis, one profile gave a subbottom consisting of a bottom bed about 1400 ft thick near the buoy with a velocity of 6100 ft/sec and a basement with a velocity of 17,000 ft/sec. The corresponding figures for the other profile were 1900 ft and 6700 ft/sec and 19,000 ft/sec. Breaks in the data suggested that bottom conditions were variable within the 6 mile length of profile.

Sound pressure data were obtained from both continuous wave (CW) and pulse (shot) sources. With A Mark 6(b) minesweeping gear as CW sources and towed hydrophones as detectors, the change of pressure with increasing range was measured for frequencies from 7-1/2 to 35 cps in 2-1/2 cps steps. The maximum ranges varied from 500 yds at the lowest frequencies up to 4000 yds at the highest frequencies. A unique hydrophone suspension (Fig. 5) permitted the units to be towed at 5-6 knots (compared with one knot in previous work) without excessive self noise. However, hydrophones suspended from a drifting boat did allow data taking to twice the range reached with the towed unit.

Comparing the CW records with theoretical predictions will require a long, rather tedious analysis. More immediate results were obtained from shot records. In agreement with the normal mode theory, the velocity of arrivals varied with frequency (dispersion) and several prominent Airy phases were recorded.

The Airy phase is the wave which arrives last. In the St. Thomas work, it had a frequency of 20 cps and a sound velocity 0.9 that of water: values which are not unreasonable. Numerical calculations(1) indicate that a sound source with the same power output at every frequency should produce a higher pressure level at the Airy phase frequency than at any other; this has been confirmed experimentally.

Analysis of the St. Thomas data is continuing but no conclusions can be drawn at present.

AMBIENT NOISE

Sound signals propagating through the ocean can be detected only if they are stronger than the ambient noise background in the ocean. The determination of this ultimate limit to sound detection is extremely important and Hudson Laboratories has been actively studying it. During the past six months, noise records obtained previously were analyzed and additional field trips made.

The analysis of seventy of the eighty-three magnetic tapes recorded aboard the USS REHOBOTH (August, 1953) indicate that in northern European waters the primary source of ambient noise is small fishing boats.

During World War II, it was found that sound propagates great distances in the deep sound channel but the level of noise in the channel was unknown. Two sets of measurements have now been made there: one, in the Tongue of the Ocean in the Bahamas; the other, twenty miles east of Eleuthera. In both cases, the "Duckling" hydrophone(2) recorded to below the sound channel axis. The data are being analyzed.

To test theories of ambient noise production and to obtain a lower limit to the absolute noise levels, noise data from a deep lake would be valuable. In March, 1954, a field party made measurements in Lake Pend Oreille, Idaho, with the generous cooperation of the David Taylor Model Basin and the Naval Electronics Laboratory, both of whom have permanent installations on the lake. Recordings were obtained at water depths as great as 950 ft and a simple array was tried. The array consisted of two duckling hydrophones spaced 25 ft apart; the analysis of the results will allow a crude determination of the coherence and directional distribution of noise in the lake.

The data have not yet been analyzed, but from monitoring the records the investigators have concluded, tentatively, that the broad band ambient noise level in the lake is 10 to 20 db below that of the ocean at sea state 0 to 1. Otherwise, the noise in the lake does not "sound" different from that in the ocean.

Up to the present, only the variation of ambient noise level with frequency has been determined. A recently completed statistical noise analyzer will show how noise amplitudes are distributed. Thirty amplitude divisions are provided within the frequency range from 5 to 100 cps. Preliminary tests of the unit were successful.

A fifteen element receiving array designed to yield the variation of ambient noise level with direction of arrival is nearing completion. It will be tested in June or July, 1954.

Two devices useful in assembling and calibrating ambient noise measurement equipment have been built. One of these, a hydrophone calibration tank (Fig. 6), depends on accelerating a long column of water. Although the system can give absolute calibrations at low frequencies, it is ordinarily used with a reference hydrophone to get relative sensitivities. The hydrophone output voltages are so great and undistorted that no amplification or 60 cps filtering are needed. The frequency range of the present motor-driven unit is 1 to 32 cps, but it is planned to raise the upper limit to 2000 cps by driving with an electromagnetic source.

The second device recently developed is a liquid-filled hydrophone. Hydrophones previously used at Hudson Laboratories had pressure-release backings and were expensive. It has been found that simple liquid filled units are equally sensitive at low frequencies and will withstand static pressures of 10,000 psi. The sensitivity seems to be independent of the liquid; castor oil, distilled water, carbon tetrachloride and mercury having been tested with equal success.

SOUND PROPAGATION STUDIES - MISCELLANEOUS

Bathymetry

The intensity of sound propagating in the ocean may be greatly reduced in crossing a seamount (see page 10). A chain of seamounts arcs southward from Cape Cod to Bermuda. The upper half of the chain has been thoroughly surveyed by WHOI ships; the lower half was investigated during a cruise of the USS ALLEGHENY in November, 1953. One new mountain was discovered at 36°18' N, 58°20' W and was named Mount Michael. It projects abruptly 10,320 ft up from a 2730 fathom abyssal plain. A second mountain, Seamount George, at 33°20' N, 60°40' W was also surveyed. This seamount is 7000 ft high and rises from an undulating part of the ocean floor, 2400 fathoms deep, northeast of Bermuda. Its presence was first inferred by Lamont Geological Observatory from echoes on Bermuda Sofar records. Seamount George had been crossed previously by a submarine which confirmed its existence but did not survey it. Significant sounding lines were made across eight other seamounts whose shapes were incompletely known. In between the seamounts, the ocean floor was found to be a flat, abyssal plain, not intermountain basins as shown on the hydrographic charts. There appears to be a slight topographic rise along the axis of the seamount chain extending southeast from Cape Cod. All of the seamounts surveyed have peaked tops; no flat-topped seamounts, or Guyots, were found.

During this same cruise, crossings were made of the Hudson canyon in 2000 fathoms of water and of the Hydrographer canyon in 1800 fathoms of water. The results confirmed the findings in previous Hudson Laboratories reports.

Montauk Point, New York

The transmission data taken in December, 1952, on the continental shelf south of Montauk Point, Long Island, have been studied further. In the frequency range 30-60 cps, the results are consistent with zero loss for bottom reflections at angles beyond the critical angle. The loss per reflection is not greater than 0.25 db.

Figure 7 compares pressure levels for each of the five octave bands between 60 cps and 2000 cps with those for the 30-60 cps band. The level in the 60-120 cps band rises a

negligible amount from 30 kyds to 115 kyds and then drops 2 db between 115 and 145 kyds. In the 125-250 cps band, the levels increase relative to those in the 30-60 cps band by about 5 db as the range increases from 30 to 115 kyds and then drop 6 db from 115 to 145 kyds. In the three octave bands between 250 cps and 2000 cps, the pressure levels slowly decrease from 30 kyds to 115 kyds and drop rapidly out to the maximum range of 145 kyds. Between 115 and 145 kyds, the firing ship entered the Gulf Stream and the surface water temperature increased from 59° F to 67° F.

The dependence on frequency of the pressure level-range relationship suggests that surface sound channel transmission contributes appreciably out to 115 kyds and that beyond 115 kyds the contribution of the sound channel diminishes rapidly. Since the curves for the 30-60 cps and 60-120 cps bands are relatively flat, surface sound channel transmission must be unimportant at these low frequencies. For higher frequency bands, the contribution of sound channel transmitted energy increases with increasing frequency until in the 1000-2000 cps band, practically all energy reaches the hydrophone via the surface sound channel. The arrival of the major portion of the 1000-2000 cps energy at travel times shorter than those for the 30-60 cps band confirms this conclusion.

For the 125-250 cps band, the bottom reflection loss is small and over the range 30 to 115 kyds the sound channel contribution more than makes up the loss. With the disappearance of the sound channel contribution, beyond 115 kyds the level drops rapidly to that produced by bottom-surface reflection transmission alone.

Bottom Reflection of Shot Pulses

Analysis of sound range data is usually complicated by reflections from the bottom or surface of the ocean. For rays which hit the bottom at angles less than the critical angle, an angle determined by the relative sound velocities in the water and bottom, total reflection occurs and the reflected pulse is distorted. Complete reflection also occurs at the surface but without distortion. An experimental investigation of the phenomena involved in bottom reflections was undertaken in August, 1953. A series of shots was fired at depths of 2 ft and at ranges out to 8000 yds. Since the explosive charges were too small to give a useable bottom-surface reflection, the direct arrival and first bottom reflection were compared. After application of several corrections, the reflection coefficients were found to be consistently greater than unity. Such values are impossible physically and are probably due to

loss of energy in the direct arrival through surface sound channel transmission and to bottom reflection amplitudes enhanced by additional reflections from subbottom beds.

Somewhat better records were furnished Hudson Laboratories by the Woods Hole Oceanographic Institution. The experimental work was done in 2700 fathom water northwest of Bermuda with near-surface charges large enough both to avoid bubble pulses and to assure a bottom surface reflection. Analysis of the data is proceeding.

Transmission of Continuous Wave Sound

Active Sonar systems using continuous wave (CW) sound will work only if the phase of the sound waves do not change markedly during transmission through the water. This persistence of phase is called phase coherence. Previous studies[2] showed that 30 cps sound can be transmitted over distances of several hundred miles in deep water without serious loss of phase coherence. Since frequencies useful in CW sonar systems are likely to be higher than 30 cps, an experimental determination of phase coherence at 300 cps was attempted.

A 4B source, which is similar in principle to a permanent magnet loud speaker, was operated in 4200 fathom water over the Puerto Rico trench. Two detection ranges were used: 550 yds and 34 miles. At 34 miles an intensity peak caused by deep ocean sound transmission was expected. The detected signal was surprisingly weak and could only be identified with certainty when the source was operated continuously for several minutes. From the observed sound pressure at near range, it was estimated that the acoustic output of the 4B was 0.1 watt instead of the 3 watts anticipated. This lowered output could have been the result of poor pressure compensation due to a leak in one of the source fittings.

Despite the low output, useful data were obtained. At 5500 yds, the 300 cps source maintained its phase coherence. There was evidence of phase coherence at the 34 mile distance also, but the signal level did not remain high enough for a sufficiently long time to permit accurate measurements.

Amplitude data were less certain than the phase records. Dips in amplitude on the level recorder resembled those found previously at 30 cps, but were closer together in time. This supports the hypothesis that the dips are interference minima, since minima should occur separated by roughly one wavelength. (The wavelength of 300 cps sound is one tenth that of 30 cps sound.)

The "Bedspring" Array [4]

Listening stations tracking distant targets receive sound signals in a tilted wedge with an opening approximately 20° wide. The exact opening of the wedge and its tilt-angle depend on the bottom profile in the neighborhood of the station and on oceanographic conditions. The usual listening array scans within a narrow horizontal wedge, but accepts all sound-noise and signal-without regard to vertical angle of arrival. If the ambient noise background received by a hydrophone is the same for all arrival angles, a marked improvement in signal-to-noise performance would be expected if the array discriminated against all sound except that in the vertical signal wedge. A simple calculation indicates a signal-to-noise improvement of three to ten which, with the usual assumptions, means a maximum detection range three to ten times greater than the present range. One way to limit the vertical acceptance angle is to use a "bedspring" or "grandstand" array. This device is shown in Fig. 8.

In the "bedspring" array each hydrophone of the usual line array is replaced by a longitudinal string of hydrophones so that the entire unit becomes instead a rectangular grid. The hydrophones have equal transverse and longitudinal spacings. Each longitudinal string acts as a single detector for horizontal scanning. However, the number of hydrophones in a string and the fixed time delays between hydrophones are determined by the tilt and the size of the desired acceptance wedge. If the entire grid is tilted to form a "grandstand" type structure, the delays between units in the strings can be eliminated.

Somewhat less effective signal-to-noise discrimination can be realized by replacing the hydrophones in a conventional array with geophones or with a bottomed array pointed toward the deep ocean.

The importance of increasing the detection range or, alternatively, lowering the amplitude of the signal which can be detected at a given range, can hardly be overemphasized. Listening stations are so expensive that any device which either increases the efficiency of planned installations or permits fewer installations for a given coverage assumes major economic and strategic value.

THEORETICAL STUDIES - MISCELLANEOUS

Since low frequency sound propagates great distances in the ocean almost without attenuation, a low frequency active sonar system is very attractive. Experiments conducted[5] during 1953 showed that at 30 cps the signal reflected or scattered from a submarine is too weak to detect. To avoid building a succession of different sources, a theoretical prediction of the amount of reflected energy expected at any given frequency has been sought. The problem actually considered was reflection from a prolate spheroid, i.e., a cigar-shaped body resembling a submarine without the superstructure. Preliminary computations have been completed, but the final answer depends on constants still to be furnished by the National Bureau of Standards.

A novel method of predicting the pressure field expected at great distances from a source has been developed for sound propagation in the many layered liquid case.

Recommendations on useful sites for listening arrays have usually come from the Propagation Committee. These recommendations are based, in large part, on ray tracing calculations covering the area in question. Ray tracing computations are simple but tedious and have occupied several computers working full time at Hudson Laboratories and elsewhere. To accelerate the rate at which rays can be traced, an IBM Card-Programmed Calculator will be rented for the use of the Propagation Committee. It will be located at Hudson Laboratories, but will be available to the other cooperating organizations.

SIGNAL-TO-NOISE PROBLEMS

Almost without exception, the absolute amplitude of sound propagating through the ocean is less important than the ratio of signal and noise amplitudes. In addition to the ambient noise studies already described, two other signal-to-noise problems have concerned Hudson Laboratories during the past six months. One of these resulted in a novel method for the detection of cavitating submarines by passive listening; the other, may lead to a secure communication system between submerged submarines.

Proposed Method for Detection by Passive Listening of Cavitating Submerged Submarine

Cavitation noise consists of broad band noise amplitude modulated by the propeller motion at frequencies equal to either the shaft or blade frequencies or both. (A signal is said to be amplitude modulated by another signal if the second signal controls the overall amplitude of the first.) The usual method of detecting the modulating signal consists of squaring or rectifying and filtering. In the new method, the noise is split and passed through two band-pass filters whose pass ranges do not overlap and are separated by at least twice the modulation frequency. The separate outputs are then squared, passed through identical low pass filters, and the DC components removed. The resulting outputs are cross-correlated, i.e., the average product is formed.

For equal waiting times, the new method appears poorer than the usual one. However, in the usual method either a bank of sharp filters or a sharp scanning filter is necessary and the signal frequency must remain constant for a time comparable to the reciprocal of the pass band of the filter. The new method does not require sharp filters and is unaffected by changes in signal frequency. Hence, the integration time involved in forming the average product can be made large enough to give a better signal-to-noise ratio than that obtainable by standard techniques. If a bank of sharp filters or a scanning filter is used with the new method, the resultant signal-to-noise ratio is the square of the value from the usual detection method.

Equipment is being built to test this method on tape recordings of cavitation noise. Forthcoming technical reports will present details of the computations and experimental results.

Secure Communication Between Submerged Submarines

One of the major unsolved problems in undersea warfare is communication between two submarines separated by distances of the order of fifty miles in a manner which is undetectable by a nearby enemy submarine. In cases where radio silence must be maintained, the communication would have to be purely sonic and it is here that the deep sound channel offers interesting possibilities. If a source situated at the axis of the deep sound channel is caused to radiate, then that fraction of the sound radiated into a narrow cone whose axis coincides with the sound channel axis will be propagated great distances with negligible attenuation. To take advantage of this phenomenon, it is only necessary to design transducers which the communicating submarines can suspend at depths corresponding to the axis of the sound channel.

Communication via the deep sound channel will be secure as well as long range if the sending transducer is an array suspended vertically at the channel axis. For an array of 23 elements spaced a half-wavelength apart, less than 2% of the radiated sound will occur in a region accessible to enemy submarines. By detecting with a second array also at sound channel depth, the receiving submarine can realize an additional 20 db improvement in signal-to-noise. Calculations based on simple and reasonable assumptions lead to an overall range of 600 miles for secure communication between two quiet submarines tracking a snorkeling enemy submarine. This proposal for secure communication via the deep sound channel is due to Dr. J. L. Worzel.

A sending array, to work at 1500 cps, is nearly completed and will be tested. The elements are cylinders of barium titanate 3" in diameter and 6" long. A detecting array being built in connection with ambient noise measurements (see page 15) will be used in the proposed communication system also.

THE YO-YO HYDROPHONE

The use of sonobuoys as sound detectors has been limited by the inherently high noise level of the units. Conventional sonobuoys are sensitive to surface disturbances and subject to strumming of the hydrophone cables. To avoid these difficulties, Hudson Laboratories have developed a modified sonobuoy called the Yo-Yo. As described in previous reports, it has a hydrophone connected to a long coil of wire which pays out freely and acts as a low frequency, spring-like suspension. The hydrophone may be made to hang in or below the surface sound channel.

In early tests, Yo-Yo's (Model 1) were able to detect a submarine at 22 miles in a calm sea but were mechanically unsatisfactory. Units (Model 2) used in a subsequent operation (August, 1953) failed overall so that no useable signals were recorded. After that operation, the vertical radiation pattern of the Yo-Yo transmitter was determined with helicopter-carried equipment. It has a single major lobe inclined 17° from the horizontal and a field strength of approximately 1000 microvolts per meter at a range of 2 miles and an altitude of 3000 ft. Numerous mechanical and electrical revisions made subsequently resulted in the present Model 4 Yo-Yo. The Model 4 Yo-Yo has a more suitable dynamic range and greater gain stability than previous models and a power output of 0.4 watt compared with the old value of 0.1 watt. The present Yo-Yo is 4 inches shorter than the Model 2 and so rigid that microphonic noise due to shock excitation of the tubes by wave action has been virtually eliminated.

Model 4 Yo-Yo's were tested during the March, 1954, operation in Puerto Rico. In a state 2 sea, a snorkeling submarine was tracked for 16 miles when it was masked by a passing DDE. In spite of the high lobe-angle of the radiation pattern, the radio range of one mile to the recording ship was easily maintained. The tracking ability of the Model 4 Yo-Yo will be tested further in a subsequent operation when it will be compared with a conventional sonobuoy modified to detect low frequency sound.

THE ANCHORED BUOY

At the price of more than a dollar per foot, the special cable required to link the hydrophones to shore represents a major expense in establishing underseas listening stations. The cable is armored to resist the bottom abrasion and biological activity which occur primarily in shallow water near shore. By eliminating the near-shore section of the cable, the anchored buoy developed at Hudson Laboratories permits simple, inexpensive wire to be used for armored cable at a great overall saving.

The anchored buoy(6) consists of a buoy anchored with a short armored cable in water deep enough to escape rough bottom and biological destruction. From the anchor, several miles of unarmored wire stretch seaward to a bottomed hydrophone assembly. The buoy contains a postamplifier and a frequency modulated radio transmitter which relays to a shore-based receiver the sounds detected by the hydrophone.

The first anchored buoy was laid off San Juan in August, 1953, but for reasons still unknown, no signal was recorded from the hydrophone. After several engineering changes designed to simplify the laying operations and to strengthen the unit, a second buoy was anchored off San Juan during February and March, 1954. Due to mechanical difficulties in handling the wire, the hydrophone was dropped in 250 fathom water instead of the desired 800 fathom water and the length of unarmored wire was only one mile. With this anchored buoy, half pound charges fired 110 miles away were clearly heard. Lofar recordings of airplanes and ships were made and a snorkeling submarine was tracked 20 miles in spite of the high background noise level usual at San Juan. The signal was lost in the trace of a passing DDE. The buoy floated for a month before being lost.

The anchored buoy is inexpensive to manufacture and easy to handle. It will permit the establishment of temporary undersea listening stations quickly and in places which would otherwise be inaccessible. As further experience is gained in its use, it seems certain that the anchored buoy will become a major tactical and scientific instrument.

PUBLICATIONS

During this period the following reports were issued:

Technical Report No. 13

15 and 30 cps sound propagation at a location near the entrance to New York Harbor, by G. E. Becker and R. O. Carlson.

October 13, 1953 — 29 p.
CONFIDENTIAL

Technical Report No. 14

Shot refraction profiles in the Atlantic Coastal Plain 6 miles east of Ambrose Lightship, by R. O. Carlson and M. V. Brown.

November 10, 1953 — 31 p.
UNCLASSIFIED

Status Report. April 1 - September 30, 1953

October 1, 1953 — 27 p.
SECRET

Technical Report No. 15

Transmission of 30 cps sound in deep water, by H. L. Poss.

December 15, 1953
SECRET

Technical Report No. 16

The far field acoustic wave produced in N parallel liquid layers by point source excitation, by Paul Reichel.

January 15, 1954 — 25 p.
UNCLASSIFIED

PUBLICATIONS

Approaches to studies of shallow water propagation, by I. Tolstoy, F. Levin and R. Frosch.

December 10, 1953
CONFIDENTIAL

These papers were accepted for publication as noted.

Tolstoy, Ivan, Wave propagation in inhomogeneous media, Part I, Layered media; Part II, Media with continuous variation of properties, (Submitted to Journal of Applied Physics, January 14, 1954).

Poss, H. L., Highly selective low frequency tuning fork filter. The Review of Scientific Instruments. March, 1954.

Berman, A., Saur, A. J., and McMahon, B., Mercury contact slip-rings for low level signal applications, The Review of Scientific Instruments. April, 1954.

Carlson, R. O., Brown, M. V., Seismic refraction profiles in the submerged Atlantic Coastal Plain 6 miles east of Ambrose Lightship. (Submitted to the Bulletin of Geological Society of America, February 15, 1954)

REFERENCES

1. Tolstoy, I., Levin, F. K., Frosch, R.A., Approaches to studies of shallow water sound propagation. Columbia University, Hudson Laboratories. December 10, 1953.

2. Columbia University, Hudson Laboratories, Status Report, April 1, 1953 to September 30, 1953. October 1, 1953.

3. Poss, H. L., Transmission of 30 cps sound in deep water. Columbia University, Hudson Laboratories, Technical Report No. 15. December 15, 1953.

4. Nierenberg, W. A., The "bed-spring" array. Columbia University, Hudson Laboratories, Informal Memorandum. December 10, 1953.

5. Same as Reference 2.

6. Same as Reference 2.

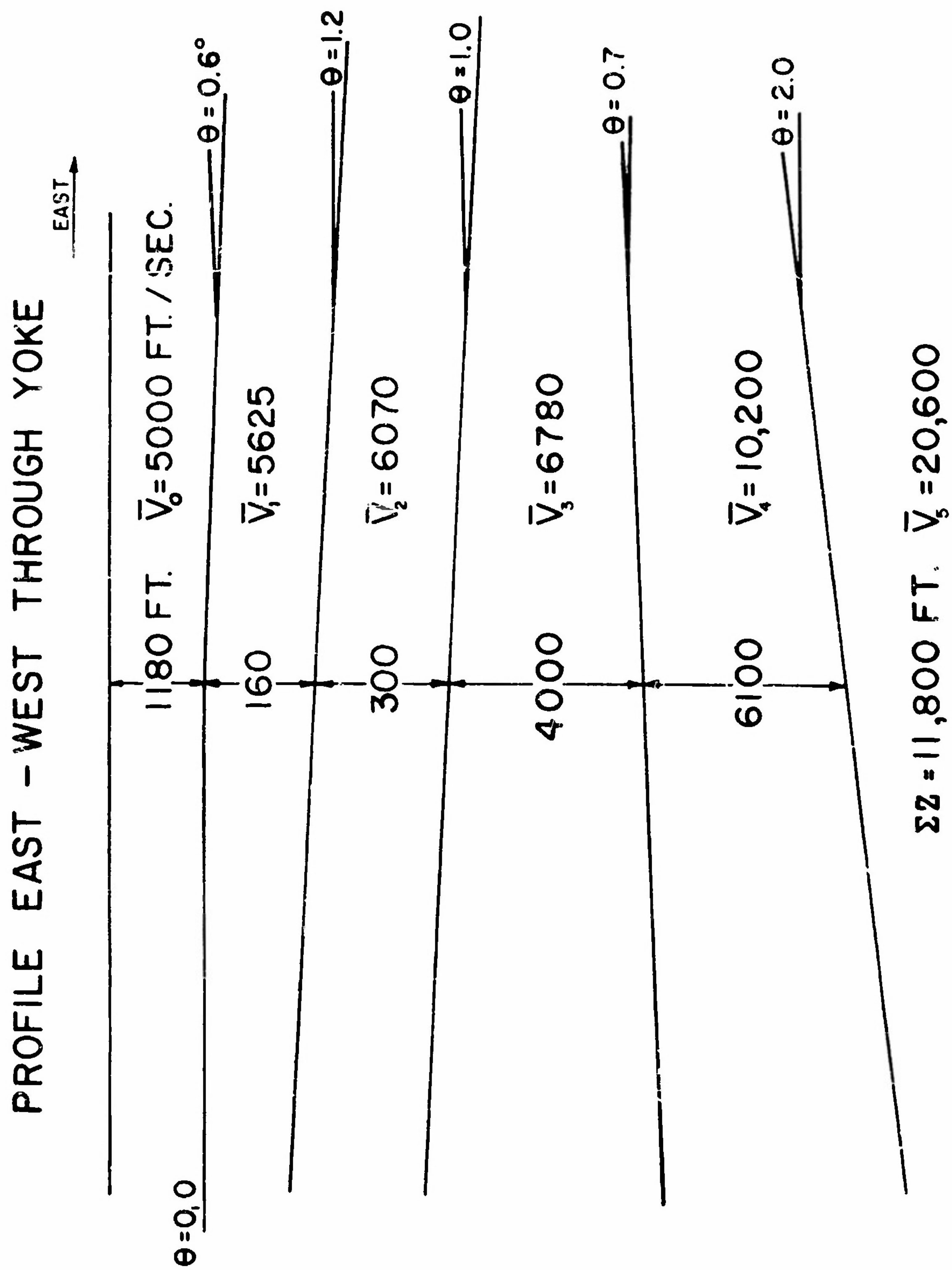

PROFILE EAST - WEST THROUGH YOKE
EAST
1180 FT.
$\bar{V}_0$ = 5000 FT. / SEC.
160
$\bar{V}_1$ = 5625
300
$\bar{V}_2$ = 6070
4000
$\bar{V}_3$ = 6780
6100
$\bar{V}_4$ = 10,200
ΣZ = 11,800 FT.
$\bar{V}_5$ = 20,600
θ = 0.0
θ = 0.6°
θ = 1.2
θ = 1.0
θ = 0.7
θ = 2.0

FIG. 1

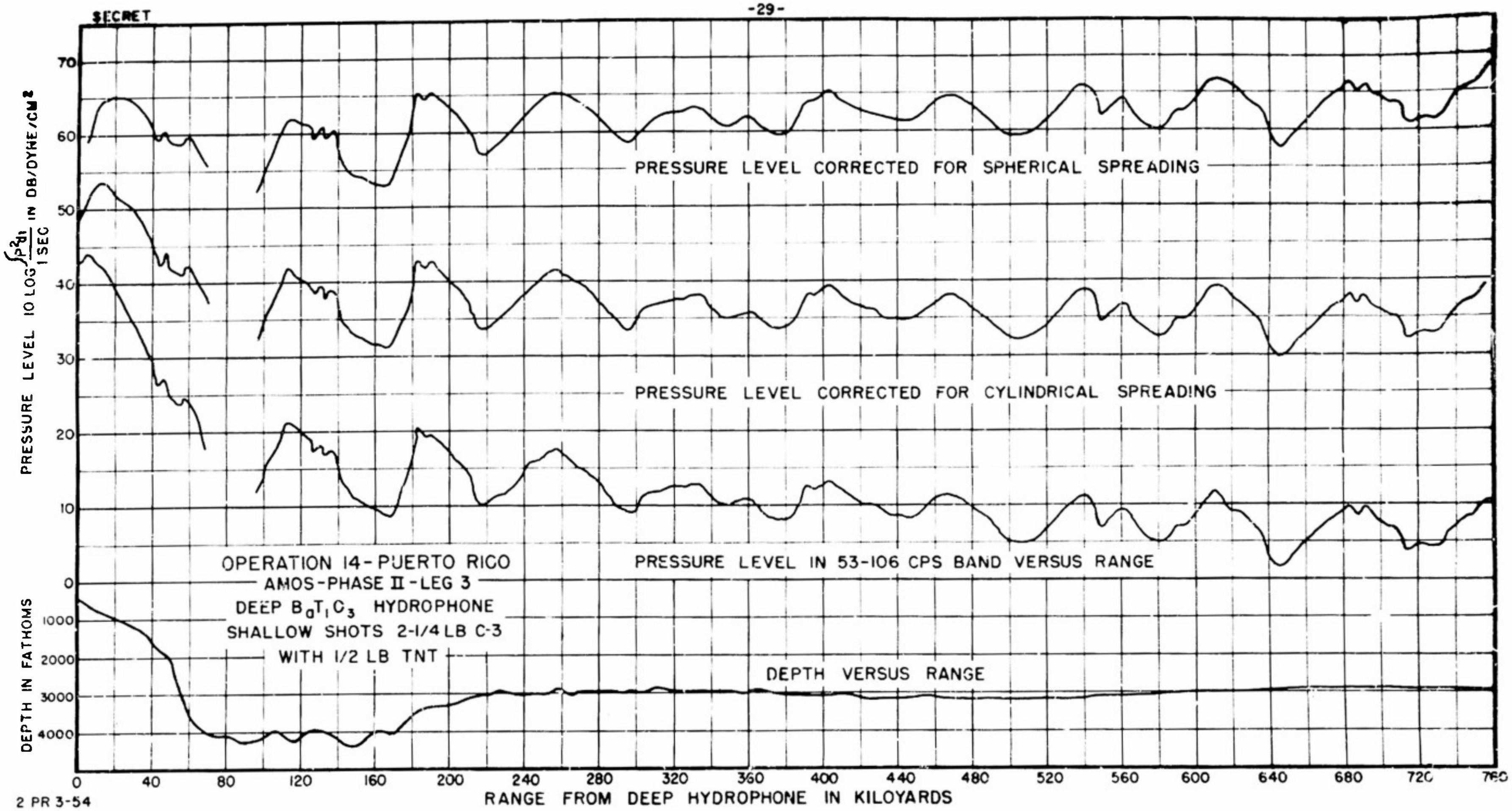
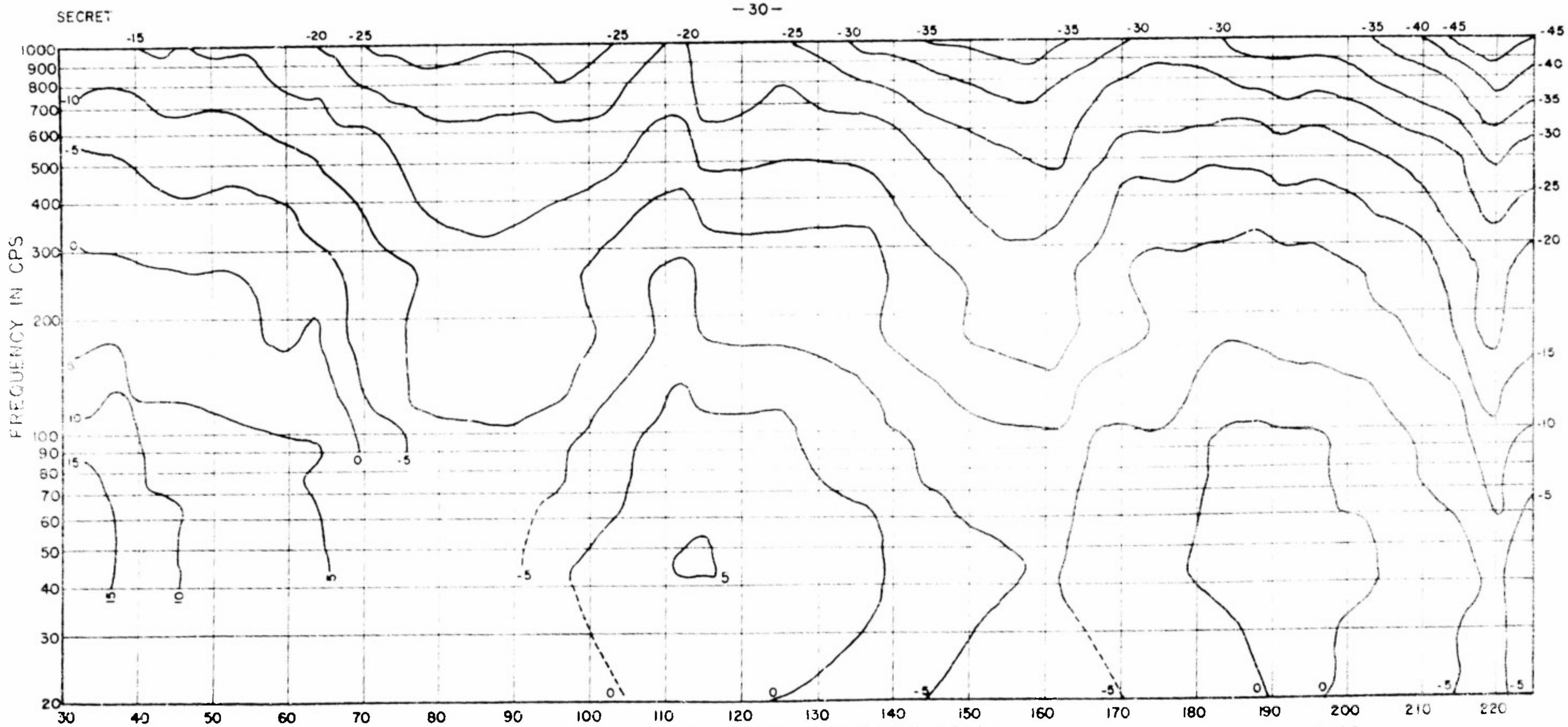

PRESSURE LEVEL 10 LOG $\frac{\int p^2 dt}{1 SEC}$ IN DB/DYNE/CM²
70
60
50
40
30
20
10
0
PRESSURE LEVEL CORRECTED FOR SPHERICAL SPREADING
PRESSURE LEVEL CORRECTED FOR CYLINDRICAL SPREADING
PRESSURE LEVEL IN 53-106 CPS BAND VERSUS RANGE
OPERATION 14-PUERTO RICO
AMOS-PHASE II-LEG 3
DEEP $B_aT_1C_3$ HYDROPHONE
SHALLOW SHOTS 2-1/4 LB C-3
WITH 1/2 LB TNT
DEPTH VERSUS RANGE
DEPTH IN FATHOMS
1000
2000
3000
4000
0
40
80
120
160
200
240
280
320
360
400
440
480
520
560
600
640
680
720
760
RANGE FROM DEEP HYDROPHONE IN KILOYARDS
2 PR 3-54

FIG. 2

SECRET



PRESSURE LEVEL CONTOUR MAP
SAN JUAN, P.R.
OPERATION 14 - AMOS CRUISE - 005° T
2-1/4 LB C-3 PLUS 1/2 LB TNT CHARGES
FIG. 3

NUMBERS GIVE PRESSURE LEVEL
$10 \log \frac{\int p^2 dt}{\Delta f \times 1 \text{ SEC}}$ IN DB/DYNE/CM^2
WHERE Δf = HALF OCTAVE FILTER BAND WIDTH

1 FR 3-54

SECRET

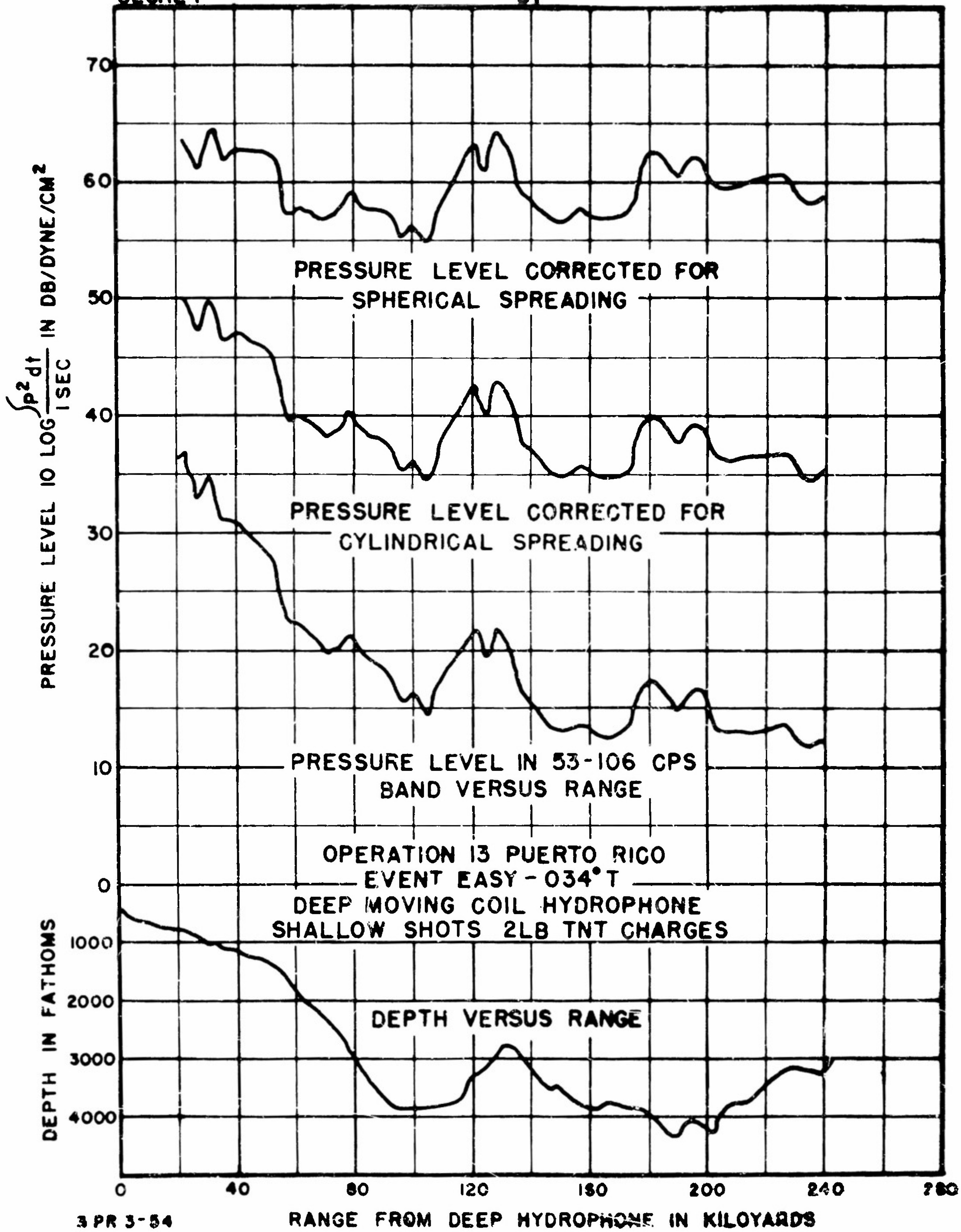
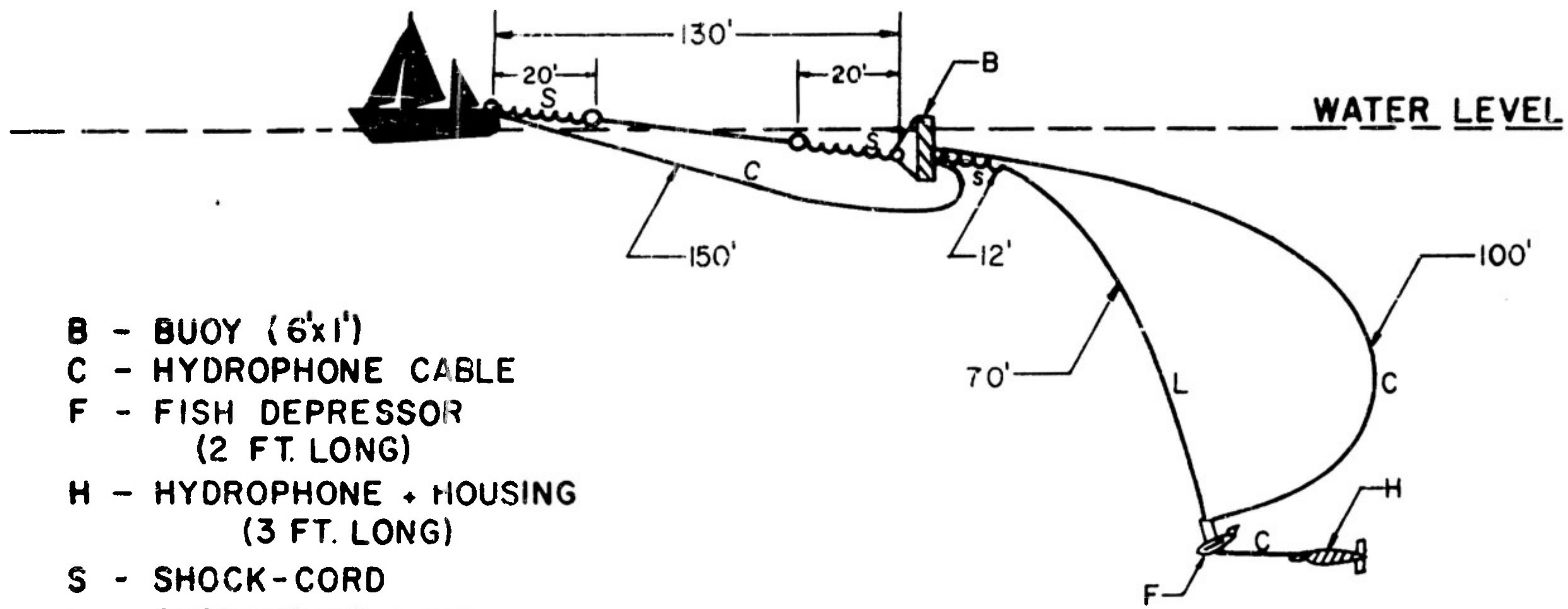

PRESSURE LEVEL 10 LOG $\frac{\int p^2 dt}{1 SEC}$ IN DB/DYNE/CM^2
70
60
50
40
30
20
10
0
PRESSURE LEVEL CORRECTED FOR SPHERICAL SPREADING
PRESSURE LEVEL CORRECTED FOR CYLINDRICAL SPREADING
PRESSURE LEVEL IN 53-106 CPS BAND VERSUS RANGE
OPERATION 13 PUERTO RICO
EVENT EASY - 034° T
DEEP MOVING COIL HYDROPHONE
SHALLOW SHOTS 2LB TNT CHARGES
DEPTH IN FATHOMS
1000
2000
3000
4000
DEPTH VERSUS RANGE
0
40
80
120
160
200
240
280
RANGE FROM DEEP HYDROPHONE IN KILOYARDS
3 PR 3-54

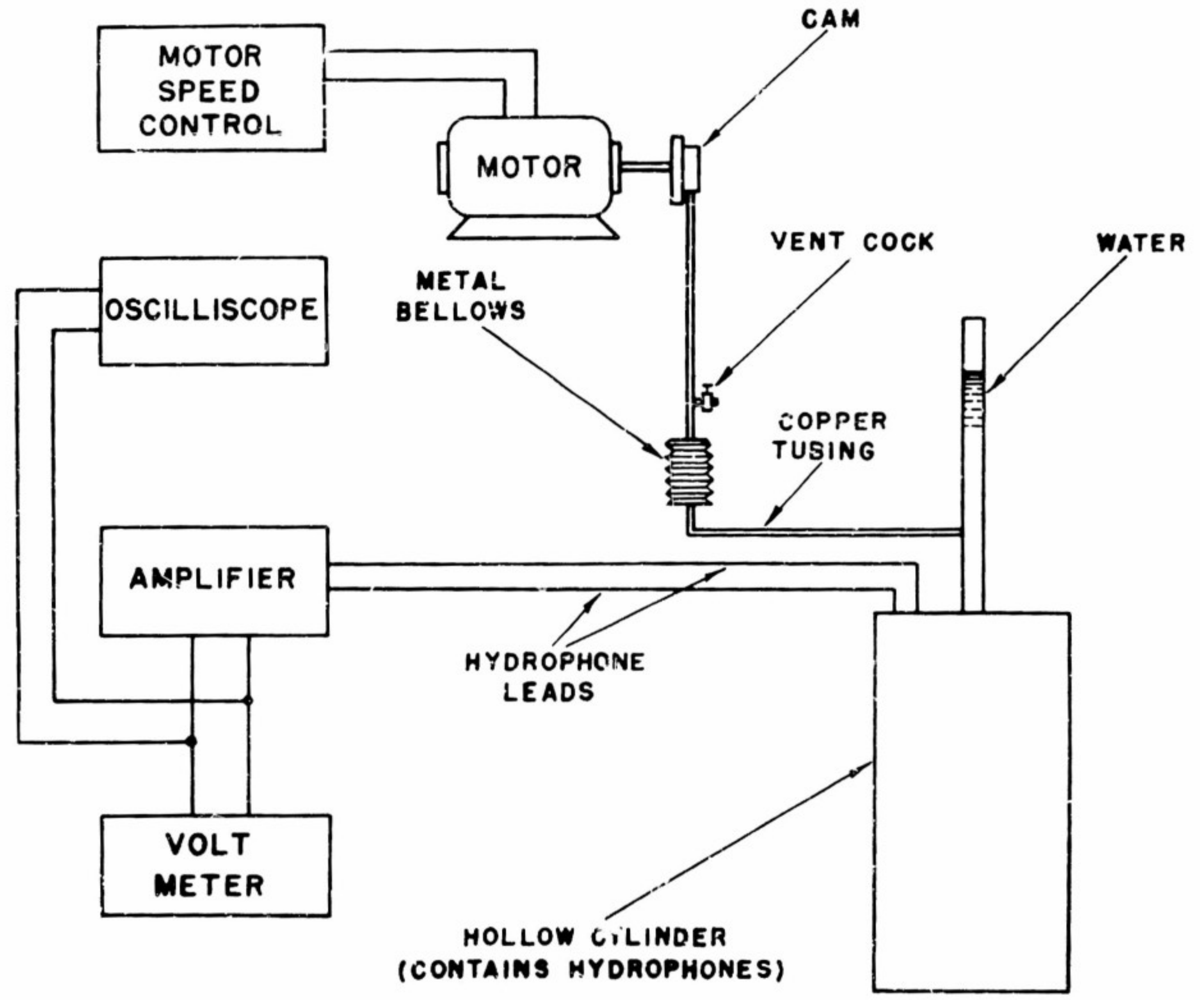
FIG. 4



B - BUOY (6'x1')
C - HYDROPHONE CABLE
F - FISH DEPRESSOR
(2 FT. LONG)
H - HYDROPHONE + HOUSING
(3 FT. LONG)
S - SHOCK-CORD
L - SUSPENDING LINE

SYSTEM FOR AX58 HYDROPHONE TOWING

FIG. 5



HYDROPHONE CALIBRATION SYSTEM

FIG. 6

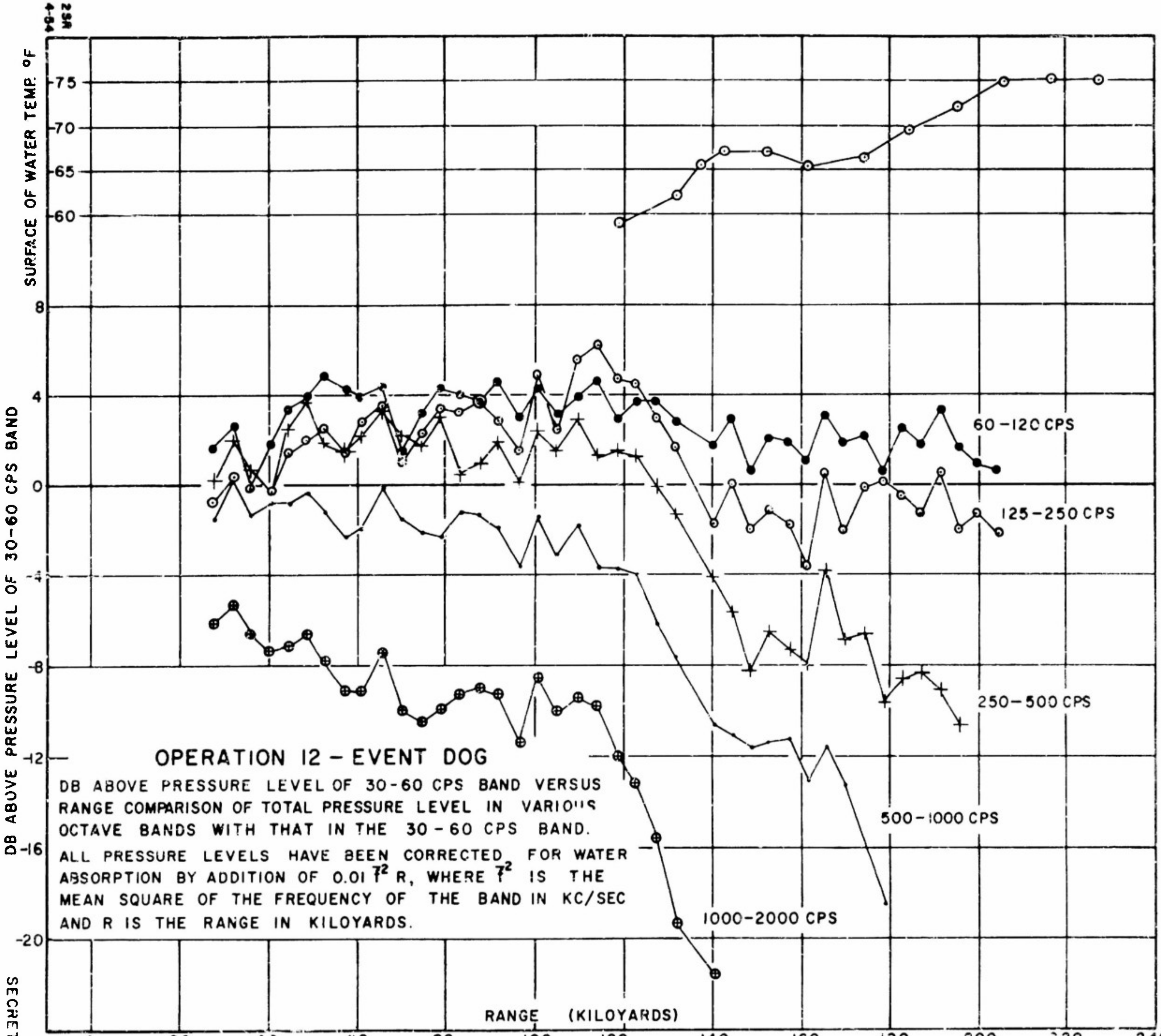
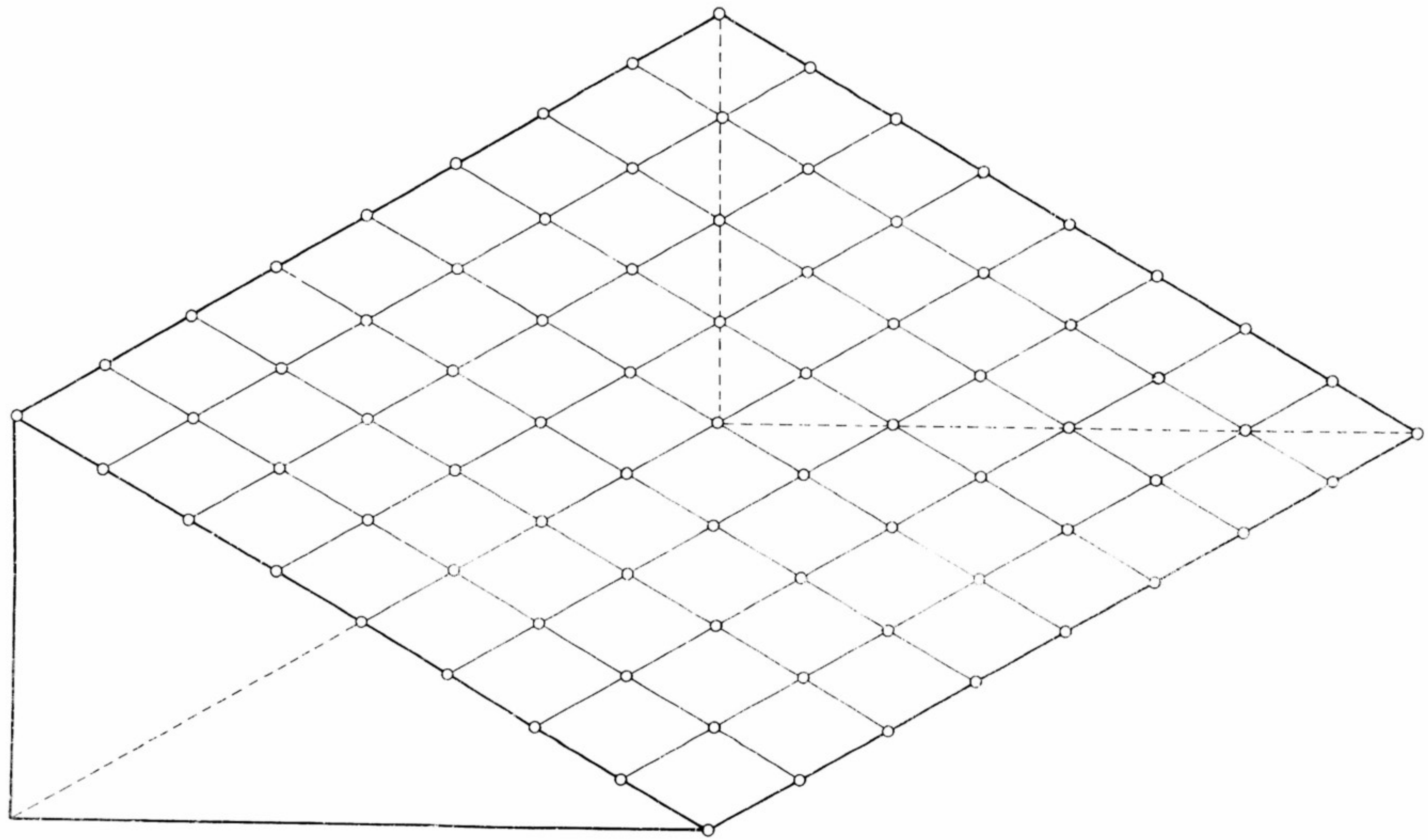

2SR
4-54
SURFACE OF WATER TEMP. °F
75
70
65
60
DB ABOVE PRESSURE LEVEL OF 30-60 CPS BAND
8
4
0
-4
-8
-12
-16
-20
60-120 CPS
125-250 CPS
250-500 CPS
500-1000 CPS
1000-2000 CPS
OPERATION 12 - EVENT DOG
DB ABOVE PRESSURE LEVEL OF 30-60 CPS BAND VERSUS RANGE COMPARISON OF TOTAL PRESSURE LEVEL IN VARIOUS OCTAVE BANDS WITH THAT IN THE 30-60 CPS BAND.
ALL PRESSURE LEVELS HAVE BEEN CORRECTED FOR WATER ABSORPTION BY ADDITION OF 0.01 $\bar{f}^2$ R, WHERE $\bar{f}^2$ IS THE MEAN SQUARE OF THE FREQUENCY OF THE BAND IN KC/SEC AND R IS THE RANGE IN KILOYARDS.
RANGE (KILOYARDS)
0
20
40
60
80
100
120
140
160
180
200
220
240

FIG. 7



THE "BED-SPRING" ARRAY

FIG. 8

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